

Production of mini-(gluon)jets and strangeness enhancement in pA and AA collisions at relativistic energies

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Abstract

The idea that effective string tension increases as a result of the hard gluon kinks on a string is applied to study the strange particle production in proton-nucleus and nucleus-nucleus collisions. It is found that the effective string tension increases with the increase of centrality and mass of the colliding system as a consequence of the mini-(gluon)jet production stemming from the collective string-string interaction. This mechanism leads to strangeness enhancement in pA and AA collisions through the enhanced production of the strange quark pairs from the color field of strings. We discuss different roles played by this mechanism and rescattering of the final state hadrons in the production of strange particles and compare our results with experimental data.

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1 Introduction

Strangeness as a possible signature of the phase transition from a hadronic state to a QGP state was put forward about 15 years ago [1]. It was based on the prediction that the production of strange quark pairs would be enhanced as a result of the approximate chiral symmetry restoration in a QGP state in comparison with a hadronic state. The strangeness enhancement in pA and AA collisions with respect to the nucleon-nucleon collision has been investigated and confirmed by many experimental groups [2][3] [4][5]. However, alternative explanations exist in the hadronic regime, like rescattering, string-string interaction, etc. [6][7][8]. The first detailed theoretical study of strangeness production can be found in [9].

We have done a series of studies in recent years investigating strangeness enhancement based on a rescattering scheme [6][10] [11], from which a Monte-Carlo event generator, LUCIAE, was developed [12]. Those studies indicate that including rescattering of the final state hadrons is still not enough to reproduce the NA35 data of strange particle production, which imply enhanced production of strange quark pairs in nucleus-nucleus collisions. To reproduce the NA35 data needs further to rely on the reduction of strange quark suppression in nucleus-nucleus collisions comparing to the nucleon-nucleon collision [10][11]. Similarly, in order to reproduce the NA35 data, the RQMD generator, equipped with rescattering though, has to resort to the colour rope mechanism [8]. In this picture it is assumed that the neighboring interacting strings might form a string cluster called colour rope in pA and AA collisions. The colour rope then fragments in a collective way and tends to enhance the production of the strange quark pairs from the colour field of strings through the increase of the effective string tension.

It has been known for years that the strange quark suppression factor (λ hereafter), i.e. the suppression of s quark pair production in the color field with respect to u or d pair production, in hadron-hadron collisions is not a constant, but energy-dependent, increasing from a value of 0.2 at the ISR energies to about 0.3 at the top of the SPS energies [13]. In [14] we proposed a scenario to investigate the energy dependence of λ in hh collisions by relating the effective string tension to the production of hard gluon jets (mini-jets). A parametrization form was then obtained, which reproduces the energy dependence of λ in hh collisions reasonably well. By taking the energy dependence of λ (and the other parameters related to the effective string tension) into account our model reproduce nicely the data of strange particle production in hh collisions.

We have in [10][11] described successfully the NA35 data of pA and AA collisions based on the idea of reduction of strangeness suppression via adjusting the concerned parameters λ etc. relating to the effective string tension. The relations between the reduction of strangeness suppression (the parameter λ etc.) and effective string tension are thus urgent to be established. In this work we use the idea of [14] and the Firecracker model [15] to study above relations. The study reveals that the mini-jet production from the string-string interaction might play a role in the strangeness production. It causes the strange quark suppression factor increasing with centrality and mass of the colliding system in nucleus-nucleus collisions in addition to increasing with energy (such kind of the strange quark suppression factor increasing with energy, centrality, and mass of the colliding system is called as reduction mechanism of s quark suppression hereafter). This study provides then a dynamic explanation for the reduction of strangeness suppression shown in the experimental data of nucleus-nucleus collisions.

2 Brief review of LUCIAE model

LUCIAE model is developed based on the FRITIOF model [16]. FRITIOF is a string model, which started from the modeling of inelastic hadron-hadron collisions and it has been successful in describing many experimental data from the low energies at the ISR-regime all the way to the SPS energies [17] [18]. In this model a hadron is assumed to behave like a massless relativistic string corresponding to a confined color force field of a vortex line character embedded in a type II color superconducting vacuum. A hadron-hadron collision is pictured as the multi- scatterings of the partons inside the two colliding hadrons. In FRITIOF, during the collision two hadrons are excited due to longitudinal momentum transfers and/or a Rutherford Parton Scattering (RPS). The highly excited states will emit bremsstrahlung gluons according to the soft radiation model. They are afterwards treated as excitations i.e. the Lund Strings and allowed to decay into final state hadrons according to the Lund fragmentation scheme [19].

The FRITIOF model has been extended to also describe hadron-nucleus and nucleus-nucleus collisions by assuming that the reactions are superpositions of binary hadron-hadron collisions in which the geometry of the nucleus plays an important role because the nuclei should then behave as a “frozen” bag of nucleons.

However in the relativistic nucleus-nucleus collision there are generally many excited strings formed close by each other during a collision. Thus in LUCIAE a Firecracker model is proposed to deal with the string-string collective interaction. In the Firecracker model it is assumed that several strings from a relativistic heavy ion reaction will form a cluster and then the strings inside such a cluster will interact in a collective way. We assume that the groups of neigh-

bouring strings in a cluster may form interacting quantum states so that both the emission of gluonic bremsstrahlung as well as the fragmentation properties can be affected by the large common energy density, see [15] for the details.

In relativistic nucleus-nucleus collision there are generally a lot of hadrons produced, however FRITIOF does not include the final state interactions. Therefore in LUCIAE a rescattering model is devised to consider the interactions of produced hadrons with each other and with the surrounding cold spectator matter. The distributions of the final state hadrons will be affected by the rescattering process. The details have been described in [10] and [12], here we just give the complete list of the reactions including in LUCIAE, which are cataloged into:

$$\begin{array}{ll}
\pi N \rightleftharpoons \Delta\pi & \pi N \rightleftharpoons \rho N \\
NN \rightleftharpoons \Delta N & \pi\pi \rightleftharpoons k\bar{k} \\
\pi N \rightleftharpoons kY & \pi\bar{N} \rightleftharpoons \bar{k}\bar{Y} \\
\pi Y \rightleftharpoons k\Xi & \pi\bar{Y} \rightleftharpoons \bar{k}\bar{\Xi} \\
\bar{k}N \rightleftharpoons \pi Y & k\bar{N} \rightleftharpoons \pi\bar{Y} \\
\bar{k}Y \rightleftharpoons \pi\Xi & k\bar{Y} \rightleftharpoons \pi\bar{\Xi} \\
\bar{k}N \rightleftharpoons k\Xi & k\bar{N} \rightleftharpoons \bar{k}\bar{\Xi} \\
\pi\Xi \rightleftharpoons k\Omega^- & \pi\bar{\Xi} \rightleftharpoons \bar{k}\bar{\Omega}^- \\
k\bar{\Xi} \rightleftharpoons \pi\bar{\Omega}^- & \bar{k}\Xi \rightleftharpoons \pi\Omega^- \\
\bar{N}N \text{ annihilation} & \\
\bar{Y}N \text{ annihilation} &
\end{array}$$

where Y refers to the Λ or Σ and Ξ refers to the Ξ^- or Ξ^0 . There are 364 reactions involved altogether.

3 Results and discussions

String tension is defined as the energy per unit length of the string. However, the existence of gluons on the string (regarded as the transverse excitation or ‘kink’ on a string in the Lund string fragmentation model) would wrinkle a string and give a fractal structure. Such a wrinkled string has larger energy density in comparison with a string without gluon, thereby an enhanced string tension effectively [20].

The following form has been used in [14] to parametrize the relation between the effective string tension and the hard gluon jets on a string

$$\kappa_{eff} = \kappa_0(1 - \xi)^{-\alpha}, \quad (1)$$

where κ_0 is the string tension of the pure $q\bar{q}$ string, α is a parameter to be determined by experiments and ξ is calculated by

$$\xi = \frac{\ln(\frac{k_{\perp}^2_{max}}{s_0})}{\ln(\frac{s}{s_0}) + \sum_{j=2}^{n-1} \ln(\frac{k_{\perp}^2_j}{s_0})}, \quad (2)$$

which represents the scale that a multigluon string is deviated from a pure $q\bar{q}$ string. Here the multigluon string state has $(n-2)$ gluons, indexed in a colour connected way from the q (index 1) to the \bar{q} (index n) and $k_{\perp j}$, $j=2, \dots, (n-1)$, are the transverse momenta of the emitted gluons with $k_{\perp j}^2 \geq s_0$. The parameter $\sqrt{s_0}$ is of the order of a typical hadron mass. The parameter α in Eq.(1) and the $\sqrt{s_0}$ in Eq.(2) are determined by hh data to be about 3.5 and 0.8 GeV, respectively [14].

In the Lund string fragmentation model, the $q\bar{q}$ pairs with the quark mass m and the transverse momentum p_t are produced from the colour field of a string by a quantum tunneling process with

probability

$$\exp\left(\frac{-\pi m^2}{\kappa_{eff}}\right) \exp\left(\frac{-\pi p_t^2}{\kappa_{eff}}\right). \quad (3)$$

The above equation shows that the probability of the $s\bar{s}$ pair production with respect to a $u\bar{u}$ (or $d\bar{d}$) pair as well as the probability of a high p_t $q\bar{q}$ pair production will be enhanced in a field with larger κ_{eff} .

Assume that the width of the Gaussian transverse momentum distribution of $q\bar{q}$ pairs and the strangeness suppression factor of a string with effective string tension κ_{eff1} are σ_1 and λ_1 , respectively, then those quantities of a string with effective string tension κ_{eff2} can be calculated from Eq.(3), i.e.

$$\begin{aligned} \sigma_2 &= \sigma_1 \left(\frac{\kappa_{eff2}}{\kappa_{eff1}} \right)^{1/2} \\ \lambda_2 &= \lambda_1 \frac{\kappa_{eff1}}{\kappa_{eff2}}. \end{aligned} \quad (4)$$

We see that σ and λ for two string states are related by the ratio of the effective string tensions of this two string states only. It should be noted that the discussion above is also valid for the production of the diquark pairs from the string field, i.e. the production of the diquark pairs with respect to the $q\bar{q}$ pairs will be enhanced from a string with larger κ_{eff} , therefore, more baryons (or antibaryons) will be formed in the final state.

In JETSET routine which runs together with LUCIAE event generator, there are model parameters PARJ(2) (the same as λ) and PARJ(3). PARJ(3) is the extra suppression of strange diquark production compared to the normal suppression of strange quark pair. Both PARJ(2) and PARJ(3) are responsible for the s quark (diquark) suppression and related to the effective string tension. Besides λ and PARJ(3) there is PARJ(1), which stands for the sup-

pression of diquark-antidiquark pair production in the color field in comparison with the quark-antiquark pair production and is related to the effective string tension as well. How these three parameters affect the multiplicity distribution of final state particles can be found in [10] [11]. Another parameter PARJ(21) (the same as σ), which is the width of the Gaussian transverse momentum distribution of $q\bar{q}$ pairs in the string fragmentation, varies with κ_{eff} too, but it is not related to the strangeness production directly.

It has been shown in [10] [11] [21] and [22] that the string fragmentation by JETSET with default values of PARJ(1)=0.1, PARJ(2)=0.3 and PARJ(3)=0.4 overestimates the yield of strange particles in the pp collision at 200 GeV/c. Thus in [14] we first retune these parameters by comparing with the pp data of strange particle production [23]. A new set of parameters PARJ(1)=0.046, PARJ(2)=0.2, PARJ(3)=0.3 and PARJ(21)=0.32 GeV/c (the corresponding default value is 0.37 GeV/c) are found for pp at 200 GeV/c. This set of parameters are then used to calculate the particle production in pA and AA collisions at 200 GeV/c per nucleon using LUCIAE event generator including the reduction mechanism of s quark suppression.

In hh collisions there are two strings formed before fragmentation. The λ values calculated above are the mean value of the two strings. When we talk about λ and the other parameters in pA and AA collisions it also mean the corresponding values averaged over all the string states formed after a collision.

When LUCIAE is used to calculate the minimum bias p-nucleus collisions and the central sulphur-nucleus collisions at 200A GeV/c, it is found that λ increases steadily with the mass of the colliding system from 0.22 for p+S to 0.28 for S+S and then the increase

approaches gradually saturation see Tab.1. The values of the other three parameters in JETSET are also listed in Tab.1. This result is encouraging since we found in [10] that in order to reproduce the NA35 data of strange production at 200A GeV/c, $\lambda \simeq 0.2$ is needed for pp and p-nucleus collisions and $\lambda \simeq 0.3$ for nucleus-nucleus collisions. We have repeated those calculations using present version of LUCIAE, the results are all close to the corresponding results in [10]. In addition, we do here compare the NA35 data of the transverse momentum and rapidity distributions of negative hadrons and participant protons in central and peripheral S+S and minimum bias isoscalar NN collisions [24] with the corresponding results of LUCIAE as shown in Fig. 1, 2 and Tab. 2. The agreement between the NA35 data and results of LUCIAE is reasonably good except that the rapidity distributions of the participant protons at the target fragmentation region is lower than the data, which might be attributed to the fact that the fragmentation of the target spectators is not included in our calculation.

Fig.3 shows how the $\bar{\Lambda}$ multiplicities in the full phase space normalized by the mean multiplicities of negatively charged particles calculated from LUCIAE for S+Pb at 200A GeV/c and Pb+Pb at 158A GeV/c vary with the increase of the centrality characterized by the mean multiplicities of negatively charged particles. The NA35 data [3] for central S+S and S+Ag collisions at 200A GeV/c are also shown in this figure together with the corresponding results of LUCIAE. It can be seen from Fig.3 that the $\bar{\Lambda}$ production with respect to the negative multiplicity from the LUCIAE calculation increases slightly with the increasing centrality. The three centralities for Pb+Pb collisions are $0.0fm < b < 3.3fm$, $3.3fm < b < 6.8fm$ and $6.8fm < b < 10.0fm$, respectively, the same as ones used in the NA50 experiment of Pb+Pb collisions[25] which claimed anomalous

J/ψ suppression and a hint of the QGP formation. The λ values calculated by LUCIAE at three above centralities are 0.277, 0.287 and 0.290, respectively. Significant deviation from the LUCIAE results in Fig.3 would be expected if the QGP phase transition does really occur in Pb+Pb collisions since the approximate restoration of the chiral symmetry will mean larger λ values in the QGP state.

It is needed to point out that the increase of the effective string tension (hence λ) with the increase of energy in hh collisions is due to the production of high k_{\perp} -gluons from either the RPS or the bremsstrahlung radiation of the colour dipoles (both of which have been included in our calculations by using FRITIOF that runs together with LUCIAE). But the increase of λ with the increase of centrality and mass of the colliding system at a given energy in pA and AA collisions is due to the collective gluon emission from the Firecracker model – the more violent a collision, the harder the emitted Firecracker gluons, thereby the larger effective string tension.

Two major sources which contribute to the production of strange particles in LUCIAE are the $s\bar{s}$ production from the string fragmentation and the rescattering of the final state hadrons. We find that the rescattering contribution to the $\bar{\Lambda}$ production is greatly restricted due to the reverse reactions and the $\bar{\Lambda}N$ annihilations. For instance, $\bar{\Lambda}$ multiplicity in the central S+S collision at 200 A GeV/c will only increase by about 5% if the cross section of the strangeness production reactions is doubled from its default value. By contrast, the strangeness production is very sensitive to λ . When a value of $\lambda=0.6$ is used to calculate the $\bar{\Lambda}$ production with respect to the negative multiplicity in the central Pb+Pb collision at 158 A GeV/c we find that the ratio is about 0.058 in comparison with 0.017 at $\lambda=0.290$, enhanced by a factor of 3.4.

The success of LUCIAE model in describing the NA35 data means that present experiments of strangeness enhancement in nucleus-nucleus collisions can be understood in the hadronic regime via the consideration of the collective effects and the final state interaction. Both the mini-jet production from the Firecracker model and the rescattering process affect the distributions of strange particles seen in experiments.

The parameters used in LUCIAE model have been, to a large extent, fixed either by experimental data or by the requirement of consistency with e^+e^- physics and hh collisions. It is encouraging that this model can successfully describe many experimental data in such a consistent way. We may be able to see the real signals of a QGP through deviations from our model if the data can not be accounted for within a reasonable margin of flexibility of the model.

In summary, we have proposed a scenario which relates the increase of the effective string tension to the mini-(gluon)jet production stemming from the string-string interaction in high energy pA and AA collisions to investigate the reduction of the strangeness suppression in nucleus-nucleus collisions as revealed by the NA35 data of strange production. This scenario provides an explanation of the enhanced production of strange quark pairs from the string fragmentation needed to understand the NA35 data in pA and AA collisions at 200A GeV/c.

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Figure Captions

Fig. 1 The rapidity distributions for (a) h^- and (b) participant proton. The N+N data and corresponding results of LUCIAE have been multiplied by 10 for ease of comparison. Labels are experimental data, histograms are corresponding results of LUCIAE.

Fig. 2 The transverse momentum distributions for (a) h^- and (b) participant proton. Labels are experimental data, histograms are corresponding results of LUCIAE.

Fig. 3 The negative multiplicity dependence of $\bar{\Lambda}$ particle in S+ Pb reaction at 200A GeV/c and Pb + Pb reaction at 158A GeV/c calculated in the full phase space from LUCIAE. The LUCIAE predictions for the central S+S and S+Ag collision at 200A GeV/c are also given in the figure. The data points are taken from [3].

Table 1. The values of four JETSET parameters in
min. bias p+A and central S+nucleus collisions at 200A GeV/c

	p+S	p+Ag	S+S	S+Ag	S+Pb
	min.bias	min.bias	central	central	central
PARJ(1)	0.0654	0.0725	0.107	0.109	0.109
PARJ(2)	0.220	0.231	0.282	0.284	0.284
PARJ(3)	0.323	0.328	0.380	0.381	0.381
PARJ(21)	0.331	0.338	0.366	0.367	0.367

Table 2. The mean multiplicities of h^- and participant proton and the mean rapidity shift of the participant proton in central and peripheral S+S collisions at 200A GeV/c

	N_{h^-}	N_p	Δy
S+S central			
Data	46.8 ± 2.5	12.8 ± 1.4	1.58 ± 0.15
LUCIAE	54.2	12.1	1.89
S+S peripheral			
Data	9.8 ± 1.0	3.1 ± 0.8	1.0 ± 0.15
LUCIAE	9.5	2.6	1.5

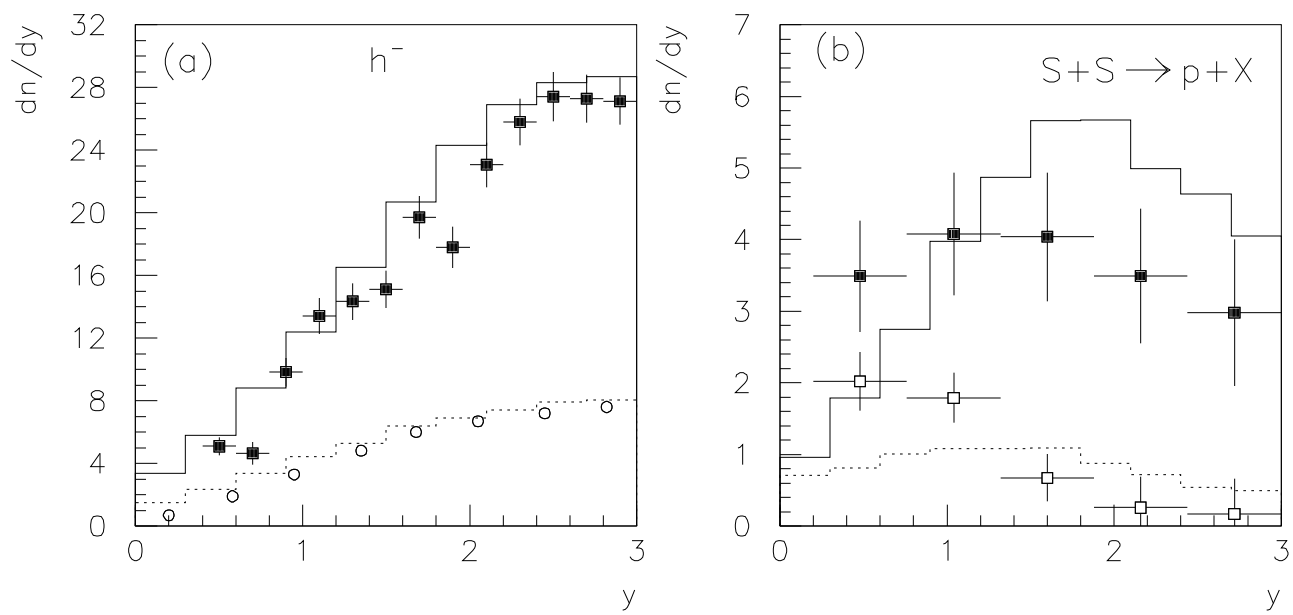


Fig. 1

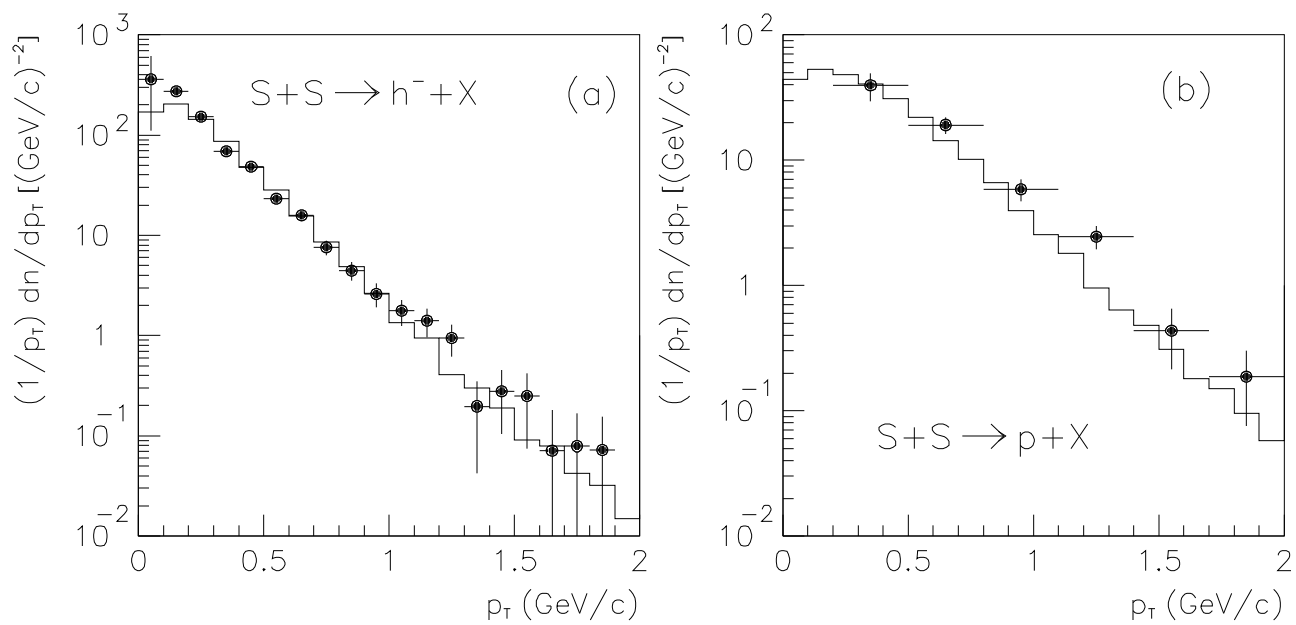


Fig. 2

